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Water management and productivity in planted forests

JAMI E. NETTLES
Weyerhaeuser Company, PO Box 2288, Columbus, Massachusetts 39701, USA
jami.nettles@weyerhaeuser.com

Abstract As climate variability endangers water security in many parts of the world, maximizing the carbon balance of plantation forestry is of global importance. High plant water use efficiency is generally associated with lower plant productivity, so an explicit balance in resources is necessary to optimize water yield and tree growth. This balance requires predicting plant water use under different soil, climate, and planting conditions, as well as a mechanism to account for trade-offs in ecosystem services. Several strategies for reducing the water use of forests have been published but there is little research tying these to operational forestry. Using data from silvicultural and biofuel feedstock research in pine plantation ownership in the southeastern USA, proposed water management tools were evaluated against known treatment responses to estimate water yield, forest productivity, and economic outcomes. Ecosystem impacts were considered qualitatively and related to water use metrics. This work is an attempt to measure and compare important variables to make sound decisions about plantations and water use.

Key words water; forests; sustainability; indicators; plantations; peak flow; base flow

INTRODUCTION

Industrial forestry operates under a broad set of demands that are constantly shifting. Climate change introduces not just new demands but additional complexity itself, which environmental research is struggling to address. In addition to traditional wood products, demand for forest-based biofuel feedstock will undoubtedly rise along with, if not due to, changes in familiar environmental feedback mechanisms. To maximize environmental protection, the practices considered to protect water resources must also include components of the carbon life cycle such as equipment efficiency and harvest residuals, and describe parameters that can be compared across industries. Environmental protection must then be balanced with social and economic concerns to achieve sustainability.

The need to respond to climate change is driving the development of sustainability metrics to describe these choices and guide decision making. While many different metrics will be needed to cover all socio-ecological impacts of land-use decisions, water use has emerged as a reasonable measure of sustainability. However, water accounting reveals underlying complications when applied. The first difficulty lies in simplifying and reconciling various philosophies of water accounting. Any attempt to quantify water use includes decisions on the definition of water use and the choice of temporal and spatial scales. Reducing complexity also obscures detail. The second is linking water use to its socio-ecological impacts. Water use matters more in areas of water stress, and metrics must have a weighting mechanism based on scarcity or demand and include relevant baseline conditions to be meaningful. The third difficulty is calculating the metrics at a scale appropriate to land-use management decisions. Reliable hydrologic predictions depend on models parameterized with site-specific variables and calibrated with historic data, but simpler metrics depend on generalizations across a wide range of conditions. Proposed water volume metrics must be integrated with available or easily acquired data and explicitly state the scale of generalization.

Several strategies for reducing the water use of forests have been published, ranging from policy guidelines for planting and species selection to site-specific management techniques such as thinning and site layout, but there is little research tying these to operational forestry. This work combines the proposed tools with application to plantation management, and calculates relevant sustainability indicators. Using data from research in the southeastern USA, water management strategies are evaluated against known treatment responses to estimate water yield, productivity, and economic outcomes.

WATER VOLUME METRICS

Water volume metrics attempt to quantify the effects of land-use changes on water volume, with very different methodologies and outcomes. In addition to the virtual water and sustainability indicator methods described below, there are others such as ecosystem services evaluation (Costanza *et al*. 1997, World Resources Institute 2005, Ninan and Inoue 2013) and fee-based regulatory systems in South Africa (Scott and Smith 1997, Albaugh *et al*. 2013) and Australia (Greenwood 2013).

Virtual water

Virtual water and water footprints report the total water used in a product life cycle – from raw material to consumption. The concept of virtual water originated to track water-intensive products from their origin to consumers in water-limited areas (Bren *et al.* 2011) and maintains the connotation of trans-boundary movement. Advocates of closely related water footprints purport the metric to be the "comprehensive indicator of freshwater resources appropriated ... measured over the full supply chain" (Hoekstra *et al.* 2009). Although this metric has been criticized as not useful and has many shortcomings, it has gained momentum through the work of the Water Footprint Network and the appeal of a number that seems analogous to a carbon footprint (Ridoutt and Pfister 2010). Other methods have been proposed, such as a revised water footprint (Ridoutt and Pfister 2010), which includes water stress factors to reflect societal and ecological impacts.

Bren *et al*. (2011) used long-term evapotranspiration (ET) derived from the Cropper's Creek paired watershed study in Victoria, Australia, to compute the virtual water content of radiata pine used for wood products, but points out that while this was an interesting exercise and showed that the virtual water content of wood was similar to values published for wheat and rice, the concept itself is flawed because of the lack of comparison to baseline conditions. Problems in the methodology, such as those outlined by Ridoutt and Pfister (2010, 2013), Frontier Economics (2008) and Jewitt and Kunz (2011), are a result of oversimplifications that make this methodology unsuitable for forest products.

Sustainability indicators

Sustainability indicators also seek to describe environmental performance, but through multiple indicators and outcomes. There are indices for governments, such as the Environmental Performance Index (Emerson *et al.* 2012) and certification systems specific to an industry, such as the Forest Stewardship Council and Sustainable Forestry Initiative. A well-received set of indicators (McBride *et al*. 2011) developed for biofuel sustainability gives three general indicators for water volume: peak flow, base flow, and consumptive water use. These categories, although still broad, add metrics that are meaningful to both society and ecology and reflect not only the vegetation ET, but hydrologic modifications due to land-use change. Comparison with field research gives specific parameters that could be good indicators of sustainable practices for planted forests for biofuel or wood products.

CALCULATING WATER VOLUME METRICS

Hydrologic predictions are built on long-term weather data, topographic information, and site specific variables. While McBride *et al.* (2011) state that sustainability indicators should be applicable for a range of scales from regional to the management tract, suggested methods refer to techniques which would be too costly for most landowners. In addition, impact estimations are needed for sites that do not adjoin streams. A practical indicator would rely on publicly available sources for long-term data and one-time sampling or a survey for site-specific parameters.

In order to understand the application of sustainability indicators to plantation forests, water volume indicators were defined and calculated with data from operational research. The Weyerhaeuser Company has a long history of cooperative forest hydrology research, with current highly instrumented paired watershed studies in the USA and Uruguay comparing the water quality and quantity effects of silviculture, biofuel plantings, and afforestation. The results of these studies include findings on many water quality and quantity parameters and appropriate syntheses, such as average annual potential ET (PET) and ET have been developed. Data for this work is primarily from the Parker Tract, a 4000 ha Weyerhaeuser Company site in North Carolina, USA, described by Chescheir *et al.* (2003). Since this analysis is looking at possible management changes for increased site water yield, the baseline is current forest management.

Peak flow

Peak flow is the highest flow rate (Q) in a channel for a given amount of precipitation. It is a measure of maximum streamflow energy, which is related to in-stream erosion and scouring of organic matter. Stream energy (E) is increased by the volume and velocity of water leaving a site, so management practices that discourage concentrated overland flow and allow rainfall to be evapotranspired, infiltrated, or slowed will reduce peak flow. Disperse flow that enters a riparian buffer is much less likely to contribute to peak flow than concentrated flow. A study of harvest in industrial pine plantations in the Georgia piedmont, including Weyerhaeuser Company lands, reports on a survey of riparian buffer breakthroughs – where flow and or sediment move through the buffer and into the stream – and finds contributing area (A), percent bare soil, and average slope to be the best predictive variables. (Rivenbark and Jackson 2004). Other methods for computing erosional energy of flow, such as in RUSLE, are based on multiple factors, including contributing area, cover and management practices, soil erodibility, and topographic variables. However, Manning's equation for overland flow:

$$V = \frac{1.49}{n} R^{2/3} S^{1/2} \tag{1}$$

is a simple equation with well-defined methods for computing surface roughness. Substituting into the equation for the specific energy of flow and assuming that the depth of flow is negligible:

$$E = \frac{V^2}{2g} + y \tag{2}$$

gives a fractional change in energy between the new land use (1) and the original (0) as:

$$\Delta E = \frac{n_0^2}{n_1^2} - 1 \tag{3}$$

There are standard tables available for selecting *n* (e.g. Chow 1959) and also well accepted procedures for determining *n* for floodplains (Arcement and Schneider 1988). These require professional judgement or site-specific knowledge, but standard values could be developed across regions and management practices.

While Manning's *n* is an attractive variable because of the history of estimation by visual methods, there are better empirical methods and theoretical models for predicting peak flow. Regional regressions and modelling studies would give site-specific insights to the interaction of topography, soils, management practices, and vegetation.

Base flow

Base flow is considered by McBride *et al*. (2011) as a measure of sustaining environmental flow for aquatic biota and availability for human consumption. As in peak flow, the baseline condition is quite important. Using base flow as a metric is problematic because many operational plots do not lie along developed channels, much less those that are intermittent or perennial. The number of zero flow days (Zhang *et al*. 2012), changes in flow duration patterns (Brown *et al*. 2005), indices of flow variability (Archer and Newson 2002, Archer 2007) or flashiness (Bennett 2013) may be appropriate to use in a research setting but cannot be quantified without multi-season data collection. In this analysis, the increase in annual yield will be a surrogate for base flow, but advances in ET measurement (Wilson *et al*. 2001) is greatly increasing our understanding of seasonal plant water use for better predictions of low flow.

Consumptive water use

Consumptive water use also captures irrigation and groundwater withdrawals in base flow determination and adds this to water use in processing. There is no irrigation in forestry, and consumptive water use in processing will not change with silvicultural practices.

MANAGEMENT FOR INCREASED WATER YIELD

Potential management strategies for increased water yield include aggressive understory suppression, especially of the hardwood understory component, and shortening the rotation length so that at any one time a smaller percentage of the plantation is mature. Managing pine stands at a low basal area is shown to significantly increase site water yield (McLaughlin *et al*. 2013), but Weyerhaeuser currently plants crop trees for sawtimber at a low stocking density. Leaving native stock or low density buffers in riparian areas with higher access to groundwater has also been proposed, but in the southeast USA, riparian buffers are managed according to state Best Management Practices which include stocking requirements.

Understory suppression

Research on a Parker Tract mid-rotation loblolly pine stand shows that understory ET is as much as 40–45% of the overall site ET (Domec *et al*. 2012), and Powell *et al*. (2005) finds a similar number in mixed pine stands in Florida. Both sites had poorly drained soils; on sites with less water, it is probable that the pines would respond more quickly to the increase in available water and the water yield increase from understory suppression would be less dramatic. Using 2005–2007 average values from the Parker Tract of 1087 mm/year ET and 1238 mm/year precipitation (P) (Sun *et al*. 2010), the increase in water yield from a more conservative reduction in site ET due to understory suppression, about 25%, would be 271 mm/year or 2.71 ML/ha/year.

Costs were approximated with the Pine Plantation Investment Calculator (Glover 2000), using timber values from eastern North Carolina (NC State University Extension Forestry 2013) on a 25 year rotation and contractor-provided costs for five aerial applications of Oust Extra at the mid-range label rate of 292.3 mL/ha (4 ounces/acre). Income to balance the loss to the internal rate of return would be US$35/ha/year, or US$13/mL water. To put this into perspective, a very influential study (Costanza *et al*. 1997) valued the water supply service of forests as US$3/ha/year (1994 US$) but a recent comprehensive review of forest ecosystem services valuation gave a global mean of US$248/ha/year (Ninan and Inoue 2013). The US Environmental Protection Association (2010) says that USA consumers typically pay around US$528/ML for water. While these numbers are not directly comparable, it does indicate that this could be economically feasible. There are many caveats – the most obvious is the unquantified ecological impact of this intensive practice. In addition, water not used upstream is not delivered in total to the downstream consumer and attenuation of the effects could be significant. Large blocks of land would have to be repeatedly treated to see a reliable source of downstream water.

As described in equation (3), the energy change ΔE will represent the peak flow metric. Applying the procedure described in Arcement and Schneider (1988) gives an initial value of Manning's n as $n = n_b + n_1 + n_2 + n_3 + n_4 = 0.020 + 0.010 + 0 + 0.020 + 0.100 = 0.150$. Reducing n_4, the vegetation parameter, to 0.075 gives an n of 0.125, for a ΔE of 45%.

Productivity would be increased by this practice. It would likely result in more sawtimber, increasing carbon sequestration.

Reduced rotation length

Reducing the rotation length has been suggested as a method of keeping a larger percentage of the forest in young or thinned trees with lower water use. Most plantations are replanted within a year of harvest and in the southern USA, trees grow and achieve full site water use rapidly. Thinning effects are generally transient, but in related research studies, they produce a significant increase in water yield. Simulation based on Parker Tract data shows thinning from 1060 to 320 trees/ha doubled the water yield (Grace *et al.* 2006). A modelling study with data from Carteret County, NC, a Weyerhaeuser loblolly plantation research site, shows "dramatic impacts" to hydrology from thinning (McCarthy and Skaggs 1992). Using the relative changes of ET described by McCarthy and Skaggs (1992) with the same Parker Tract ET and P values used by Sun *et al.* (2010) gives estimates of ET over a 25 year rotation with one thinning (Fig. 1). Shortening it to 20 years increased the average annual water yield by about 14%, an increase of 50 mm/ha/year or 0.5 ML/year. Analysis using the Pine Plantation Investment Calculator (Glover 2000) and timber values from eastern North Carolina (NC State University Extension Forestry 2013) showed no difference in the internal rate of return.

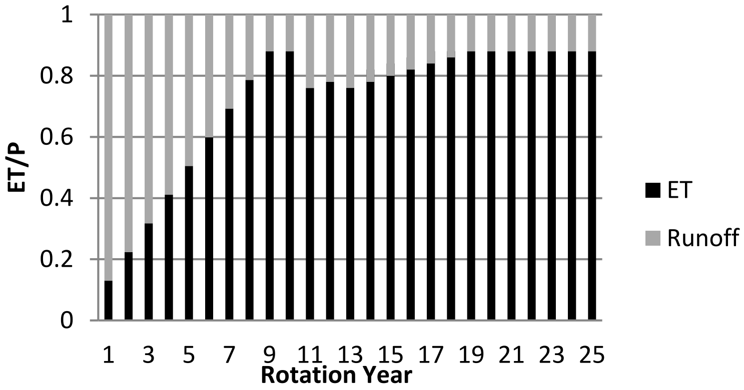

Fig. 1 Annual ET as a percent of rainfall over a forest rotation.

Using the value of n_0 used above, 0.150 and computing for post-harvest a value of $n = n_b + n_1 + n_2 + n_3 + n_4 = 0.020 + 0.010 + 0 + 0.030 + 0.01 = 0.070$, ΔE at harvest would be 3.6. Roughness would increase again after site preparation as trees are bedded and planted on the contour, so the time at reduced n would increase from 4 to 5% of the rotation under a shortened rotation. In reality, there would be intermediate states that could be measured.

Site productivity could be maintained but carbon sequestration reduced if an earlier harvest resulted in less sawtimber and more pulpwood.

CONCLUSIONS

Water volume indicators should be quantifiable with publicly available data or information that can be gathered in a site survey, and the metric should reflect the ecological impacts of a given land use. Current indicators tend to do one of these well and not the other. To calculate indicators that represent known impacts of vegetation on hydrology and land use on sustainability, simplifications must be made and tested; however, a small number of metrics can in no way represent the huge variability found even in adjacent watersheds. Without expert guidance, water volume metrics can be meaningless or counterproductive. Bren (2011) notes that consumptive use footprints create a "passion" to reduce one's impact in the way a carbon footprint does. A report by Frontier Economics (2008) states that simple virtual water concepts "promote arbitrary and inefficient policies, and lead to undesirable decisions by government." Metrics must consider the difference between water stressed and water plentiful areas or else misinform a public needing to address environmental, social and economic sustainability.

This study was an attempt to look at scenarios in the southern USA where pine plantations could be managed for lower water use. Promising water quantity sustainability indicators were applied, and economic costs evaluated. While many simplifications were made in the examples used, the methodology is replicable and could gain value by application across sites.

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